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TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 435

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OF A COMPRESSION-IGNITION ENGINE
WITH A PRECOMBUSTION CHAMBER

By C. S. Moore and J. H. Collins, jr.
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SUMMARY

The clearance distribution in a precombustion chamber cylinder head was varied so that for a constant compression ratio of 13.5 the spherical auxiliary chambers contained 20, 35, 50, and 70 per cent of the total clearance volume. Each chamber was connected to the cylinder by a single circular passage, flared at both ends, and of a cross-sectional area proportional to the chamber volume, thereby giving the same calculated air-flow velocity through each passage. Results of engine-performance tests are presented for each of the four clearance distributions to show the variations of power, fuel consumption, explosion pressure, rate of pressure rise, ignition lag, heat loss to the cooling water, and motoring characteristics.

For good performance the minimum auxiliary chamber volume, with the cylinder head design used, was 35 per cent of the total clearance volume; for larger volumes the performance improves but slightly. With the auxiliary chamber that contained 35 per cent of the clearance volume there were obtained the lowest explosion pressures, medium rates of pressure rise, and slightly less than the maximum power. For all clearance distributions an increase in engine speed decreased the ignition lag in seconds and increased the rate of pressure rise.

INTRODUCTION

The precombustion or auxiliary chamber with forced air flow for mixing fuel and air is one of the general combustion-chamber types used in compression-ignition engines.

When designing a precombustion-chamber cylinder head the influences of the variations of the different elements should be known. The precombustion-chamber position, volume, and shape, and the connecting passage area, shape, and direction have been subject to varied design treatment. The distribution of the clearance between the precombustion chamber and the cylinder is one of the fundamental variables whose effect should be determined. Theoretically, the volume of the precombustion chamber, or weight of air in it, should control the amount of precombustion if injection is confined to the chamber.

Experimental work on high-speed compression-ignition engines with precombustion chambers has been done at this laboratory by Joachim and Kemper (reference 1) and Spanogle and Moore (reference 2).

The work presented here is an experimental investigation of the effect of clearance distribution between the auxiliary chamber and the cylinder for the same relative passage restriction and compression ratio. This work was done during 1931 by the National Advisory Committee for Aeronautics at Langley Field, Va.

APPARATUS AND METHODS

The single-cylinder test engine unit with electric dynamometer shown in Figure 1 was used in this series of tests. The engine is 4-stroke-cycle, compression-ignition, of 5-inch bore and 7-inch stroke, and has the standard Liberty valve-actuating mechanism and valve timing. An N.A.C.A. universal test engine base and cylinder were used which allowed the compression ratio to be held constant as the clearance distribution was changed. The fuel-injection equipment (as in reference 2) consisted of a primary gear pump, and a cam-operated, constant-stroke, fuel-injection pump that delivered fuel to a spring-loaded injection valve having a single 0.050-inch-diameter orifice. A timing mechanism permitted the injection advance angle to be varied. Two types of injection-valve stems were used, a plain stem giving a narrow spray cone and a stem with two helical grooves of 23° angle, which gave a cone of more widely dispersed spray.

The auxiliary testing equipment was the same as for the work of reference 2 except that the balanced-pressure

apparatus (reference 3) was used to measure the maximum cylinder and chamber pressures and the improved Farnboro indicator was used to obtain indicator cards (reference 4). In this work, temperature measurements were made in both the chamber and cylinder by means of a 0.020-inch unshielded chromel-alumel thermocouple. The hot junction of the thermocouple, the locations of which are shown in Figure 2, extended about $1/2$ inch into the combustion space.

The cylinder head (fig. 2) used for these tests is so constructed that the two pieces forming the precombustion chamber and connecting passage are removable without disturbing other parts of the engine. By the construction and assembly of different chamber parts and adjustment of the compression ratio of the universal test engine, this cylinder head is easily adaptable to the investigation of a variety of combustion-chamber forms.

In this work the combustion-chamber form was not chosen to give maximum engine performance, but was designed so that the clearance could be transferred from cylinder to chamber with a minimum change in the shape of the combustion space. The cylinder clearance volume (see fig. 2) was formed between the domed cylinder head and the domed piston crown. The auxiliary chamber clearances were spherical and contained 20, 35, 50, and 70 per cent of the total clearance for a compression ratio of 13.5. For convenience of reference these clearance distributions will be called the 20, 35, 50, and 70 per cent chambers.

The connecting passages were circular in cross section, of constant length/diameter ratio, and were flared at both ends. The cross-sectional area of each of the four passages was designed to be proportional to the auxiliary chamber volume. The passage diameters were $23/64$, $15/32$, $9/16$, and $43/64$ inch for the 20, 35, 50, and 70 per cent chambers, respectively. At the same engine speeds for each of the four clearance distributions, the calculated air velocities through the passages were the same. The passage axis passed through the centers of the spheres and intersected the cylinder axis at an angle of 45° . The air flow in each of the four combustion chambers was directed counter to the fuel spray.

The cooling water entered around the bottom of the cylinder head. Part of the water rose and was discharged through an outlet in the top of the head; the rest passed

around the chamber and through an outlet in the chamber cap. Thermometers were located at the inlet to the cylinder and head and at the outlets from the cylinder, head, and chamber cap.

The standard conditions of testing were kept constant except when taken singly as variables. For convenience of reference, the conditions which were considered as standard are tabulated below.

Engine speed 1,500 r.p.m.

Compression ratio (each clearance distribution) 13.5

Fuel Diesel engine fuel, 0.847
specific gravity, 41
seconds Saybolt viscosity
at 80° F.

Full-load fuel quantity 0.0003 lb.
(12 per cent excess air) per cycle
(85 per cent volumetric efficiency)

Injection period (at 1,500 r.p.m., obtained
by Stroborama) 20° crank-
shaft

Injection advance angle (at 1,500 r.p.m.) 7° B.T.C.

Spray type Noncentrifugal

Nozzle type single orifice, 0.050 in. diameter

Fuel valve position upper chamber hole

Valve opening pressure 3,500 lb. per sq. in.

Fuel temperature 80° F.

Engine lubricating oil temperature (out) 140° F.

Cooling water temperature (out) 170° F.

Temperature of inlet air 95° F.

The test procedure was the same for each clearance distribution. The compression ratio was checked and the following motoring data taken. The f.m.e.p. was computed from the scale reading taken while the dynamometer was motoring the engine. Compression pressures were obtained from both cylinder and chamber over a speed range of 600 to 1,800 r.p.m. with both the balanced-diaphragm maximum pressure indicator and the Farnboro indicator equipment. A double indicator card at 1,500 r.p.m. was obtained by taking the chamber and cylinder records on the same sheet of paper. Motoring temperature readings at 1,500 r.p.m. were taken in the chamber and cylinder for all chamber sizes tested.

Power-test data were obtained of b.m.e.p., explosion pressures in chamber and cylinder, fuel consumptions, and heat losses to cooling water. Thermocouple temperatures were obtained for each chamber and cylinder at standard conditions and also at 900 and 1,200 r.p.m. for the 50 per cent chamber and cylinder. These data were taken at the standard fuel quantity over a range of speeds from 600 to 1,800 r.p.m. Indicator cards were also taken from the chamber and cylinder during these variable-speed tests. From the indicator cards the ignition lags and rates of pressure rise were measured. The ignition lag is considered in this report as the time in seconds from the start of injection of fuel as observed with a Stroborama to the beginning of pressure rise due to combustion as shown by inspection of the indicator card. At standard fuel quantity and engine speed, performance tests were made to determine the effect of injection characteristics. Valve-opening pressures of 2,000 and 5,000 pounds per square inch were used. With standard conditions a test was made to determine the effect of using a centrifugal spray. A test was also made at standard conditions using the noncentrifugal spray in the lower hole of the chamber cap. In addition to the tests made at full load, similar data were obtained for each clearance distribution at half load, 1,500 r.p.m. Also at 1,500 r.p.m., the fuel quantity at the start of exhaust flame was obtained for each clearance distribution by slowly increasing the load until a trace of flame appeared in the exhaust.

More detailed combustion and heat-loss data were obtained from the 50 per cent chamber because it had been used previously for a series of tests. During the testing, the barometric pressure varied from 29.49 to 30.40 inches

of mercury; the engine power data, however, were not corrected to standard pressure and temperature.

For all tests the general engine-operating characteristics were noted. Secondary tests were made to determine the starting and idling characteristics. The starting tests were made in the following manner: with the engine cold (about 70° F.) it was given two revolutions with the dynamometer. If it did not start during three such attempts, it was motored at speeds starting at 300 r.p.m. and increasing until the minimum starting speed was reached. These tests were repeated with the engine immediately after normal power operation. The engine was tested for slow speed operation by determining whether or not it would idle at 300 r.p.m.

TEST RESULTS AND DISCUSSION

Starting and idling.—The starting characteristics of the engine changed with each of the different chambers employed. None of the chambers gave starting on two revolutions of the crankshaft when cold, but starting was possible with all four of the chambers immediately after normal power operation. The minimum starting speed (compression pressure, 390 pounds per square inch) of the 20 and 70 per cent chambers when cold was 300 r.p.m.; those of the 35 and 50 per cent chambers were 800 and 600 r.p.m., respectively. The cold starting speed when using the centrifugal spray in the 50 per cent chamber was 700 r.p.m.

The idling characteristics were the same for all the chambers, idling at 300 r.p.m. being obtainable, though unsteady.

Miss to knock range.—The injection advance angle range from misfiring to allowable knocking was negligibly affected by clearance distribution when operating at standard test conditions. With the fuel valve in the lower hole of the 20 per cent auxiliary chamber the operating range increased from 12° to 27°, but the power decreased and the smoke and flame of the exhaust increased. The standard injection advance angle of 7° at 1,500 r.p.m. gave a start of pressure rise which varied from T.C. to 3° A.T.C. for all clearance distributions, as determined by inspection of indicator cards.

Table I, which follows, presents further notes on the engine-operating characteristics.

TABLE I

GENERAL OPERATING CHARACTERISTICS

Operating characteristics	20 per cent chamber	35 per cent chamber	50 per cent chamber	70 per cent chamber
Comb. knock	Dull Regular	Slight Irregular	Hard Irregular	Harder Irregular
Cyclic variation in max. explosion press.	Cham. 300 lb./sq.in. Cyl. 100 lb./sq.in.	Cham. 200 lb./sq.in. Cyl. 100 lb./sq.in.	Cham. 140 lb./sq.in. Cyl. 130 lb./sq.in.	Cham. 90 lb./sq.in. Cyl. 140 lb./sq.in.
Injection range, miss to allowable knock	12°	8°	10°	10°
Carbon deposits	Cham. - much Cyl. - little	Cham. soot and "cake" Cyl. - soot	Cham. - soot Cyl. - soot	Cham. - soft soot Cyl. - soft soot
Centrifugal spray compared to noncentrifugal spray	Knock and performance slightly worse	Knock and performance worse	Knock and performance worse	Knock and performance slightly better
Lower fuel valve position compared to upper position	Performance worse I.A.A. range 27°	No change	Performance worse	Performance worse
Optimum v.p.p.	3,500 lb./sq.in. Best	5,000 lb./sq.in. Slightly better	5,000 lb./sq.in. Slightly better	3,500 lb./sq.in. Slightly better

Effect of clearance distribution on engine performance.-

Figures 3 and 4 show that for the design of precombustion chambers used in these tests, the minimum volume in the auxiliary chamber for good performance is about 35 per cent of the total clearance volume. The inferior performance with the 20 per cent chamber can not be attributed to the non-centrifugal spray depositing fuel on the walls, because the centrifugal spray which had insufficient penetration to hit the walls gave slightly worse performance. More power was obtained with the larger chambers, because of the greater quantity of air ready for initial combustion. The air in the cylinder, being distributed over the piston crown, can not be effectively reached by the unburned gases issuing from the chamber and therefore does not materially assist the combustion process.

The connecting passage size evidently throttles the passage of burning gases during combustion more than it does the passage of air during compression. This result is indicated by the chamber explosion pressure being higher than the cylinder pressure with the small chambers. For the larger chambers with correspondingly larger passages the chamber explosion pressures are more nearly equal to the cylinder pressures. If the proportion of air in the auxiliary chamber alone were controlling the explosion pressure, the smaller chambers should have the lower pressures because theoretically there would be insufficient air for generating high combustion pressures.

Effect of clearance distribution on combustion characteristics.- Figure 5 shows that clearance distribution does not have an appreciable effect on ignition lag. This result may be expected, as the conditions of temperature, pressure, and flow velocity were held constant during the tests. The figure shows that the difference between the time of start of pressure rise in the chamber and in the cylinder is very small.

For all clearance distributions the pressure rises are straight lines (see figs. 6a and 6b) and of such high rates that it is impossible to measure them accurately; the numerical values are therefore only approximations. The trend, as the percentage distribution increases, is for the auxiliary chamber rate to decrease and for the cylinder rate to increase and then decrease. The larger chambers containing more air should give a faster rate of pressure rise because the fuel and air mixture would have more nearly the correct

proportions for complete combustion. As the opposite occurs, it indicates that the passage size is influencing the rate of pressure rise, the larger passages of the larger chambers allowing the gases to pass more freely into the cylinder.

The temperatures indicated by the thermocouples in the chamber and cylinder were indicative of the relative temperatures. The indicated combustion temperatures of the cylinder were nearly the same for all combustion chambers showing that clearance distribution had no effect on the cylinder combustion. The combustion temperature of the chamber increases with increasing chamber size because of the greater amount of air in the chamber available for combustion.

The improvement in exhaust conditions which occurs with increase of chamber proportions is caused by more air being available for initial mixing in the auxiliary chamber. Decrease in the rate of improvement with increase of clearance distribution in the auxiliary chamber above 35 per cent is due to the combination of spray shape and air flow as used in these combustion-chamber forms. This combination allows a maximum of approximately 35 per cent of the fuel to be mixed with air for efficient combustion. The remaining fuel is consumed either very late or not at all.

Effect of clearance distribution on heat loss to cooling water.— Figure 7a shows that increase in chamber volume causes the total heat loss to the cooling water to increase from 20.5 to 28.5 per cent. This increase is due to the higher combustion temperatures in the chamber and also to an increase of approximately 10 per cent in the total combustion chamber surface area. It should be noted that the total heat loss for this auxiliary chamber type of engine is less than that usually accepted for spark-ignition engines. The amount of heat loss from the chamber cap increases with chamber volume and surface, whereas the amount of heat loss from the head decreases. As more combustion occurs in the chamber with increased volume, the cylinder heat loss decreases. The similarity in shape of the "chamber cap + head" curve (fig. 7a) to the b.m.e.p. curve of Figure 3 should also be noted. As the b.m.e.p. increases the percentage heat loss to the cylinder head increases and the percentage loss to the cylinder decreases. These results indicate that the clearance distribution of the 20

per cent chamber causes late inefficient burning in the cylinder. The chamber cap and head together lose more heat than the cylinder because of the higher temperatures and longer time available for heat transfer.

Figure 7b shows that for the 50 per cent chamber the percentage heat losses to the cooling water are but slightly influenced by injection advance angle or engine speed, but are influenced to a greater degree by fuel quantity.

Effect of clearance distribution on motoring characteristics.— Figure 8 shows that the motoring characteristics remain nearly constant as the clearance distribution varies. Because less air is moved through the passage for the smaller chambers, the f.m.e.p. should be less; the decrease in f.m.e.p., however, is slight. Therefore, the work of moving the air into the chambers is but a negligible part of the total friction loss. The maximum indicated compression pressures are higher in the chambers than in the cylinder, as was previously reported for the same type of combustion chamber. (Reference 2.) The variation in compression pressure between the four chambers is probably due to experimental error although the upward trend of the cylinder pressure curve is possibly caused by the increase in the effective cylinder compression ratio as the chamber proportion increases. The indicated air temperature of the chamber is higher than that of the cylinder, possibly because the chamber air is heated by friction on being forced through the passage or because the thermocouple is partly shielded from the inlet air.

Thirty-five per cent chamber. — The 35 per cent chamber in which the weight of air would be less than 35 per cent due to throttling of the air by the throat, approaches the clearance distribution which would give the partial combustion required by the precombustion principle. There is only enough air in the chamber to allow 35 per cent of the fuel to burn in the chamber and to expel the remaining fuel into the cylinder. The test results show that for this chamber volume there is some combustion control as indicated by the low explosion pressures.

The combustion knock is slight and the rates of pressure rise as determined from the indicator cards are comparatively low and nearly the same for the chamber and cylinder. The heat loss to the cooling water is also small, being only 21 per cent of the total heat input. Comparing

the above characteristics with those of the other chamber sizes tested, it can therefore be seen that the 35 per cent chamber distribution gives the best combustion control with a minimum sacrifice in power.

Effect of speed on mean effective pressures, fuel consumption, explosion pressure, and motoring characteristics (all chambers). - Figure 9 shows the general effect of engine speed and air-flow velocity on m.e.p. and fuel consumption. The effect is nearly the same for all the chambers with the optimum speed varying from 800 to 1,200 r.p.m. The larger chambers, because of a more intimate mixture of a larger quantity of fuel and air, developed the most power and the best fuel economy. It is believed that the great difference shown by the curves for the 20 per cent chamber was caused by insufficient air in the small chamber.

The explosion pressures of all chambers (fig. 10) increase with speed because of the better mixing of fuel and air and resultant faster burning. As the engine speed increases the air-flow velocity increases and the fuel-spray dispersion increases slightly, thereby promoting better mixing. The 20 per cent chamber with small passage area confines the pressure to the chamber, giving the high chamber and low cylinder pressures as shown.

Figure 11 shows that the variation between the f.m.e.p. of the different chambers is negligible. The compression pressure peaks at approximately 1,500 r.p.m. because of the induction system characteristics. The pressure differences between chamber and cylinder vary but little for the different clearance distributions and indicate that the restrictions of the passages to the compression of the air are nearly constant.

Effect of speed on combustion characteristics (50 per cent chamber). - Figure 12 shows that engine speed has marked effects on the combustion characteristics of the 50 per cent chamber. Cards from the other three combustion chambers gave trends similar to those shown in Figure 12. As the engine speed increases the velocity of air flow in the passage increases and the mixing of fuel and air in the chamber is more complete with more rapid combustion and higher rates of pressure rise. The successive engine cycles varied as the engine sound clearly indicated, so that the points on the Farnboro indicator cards are widely dispersed, especially at the pressure peaks. The rates of

pressure rise obtained are the maximum, since only the leading points are taken. Apparently the rate of pressure rise and knock do not vary together, because the rates of pressure rise are less at the lower speeds and the combustion knock audibility remained constant.

The point of start of pressure rise is dependent upon the injection advance angle which is the earliest permitted by allowable knock intensity. The start of pressure rise varies from approximately 10° A.T.C. at 600 r.p.m. to 2° A.T.C. at 1,800 r.p.m. The ignition lag measured in seconds is reduced one-half by an increase in engine speed from 600 to 1,200 r.p.m., primarily because of the better fuel and air mixing caused by higher velocity of air flow.

The combustion temperatures as measured by thermocouples in the chamber and cylinder show an increase in temperature with speed. It is believed that this trend towards higher temperatures at increased speed is due to better combustion caused by the increased velocity of air flow with speed. This observation can not be definitely stated because of the lack of sensitiveness of the thermocouples used in this work.

Motoring indicator card. - Figure 13 shows a double indicator card taken at 1,500 r.p.m. when using the 50 per cent chamber assembly. The differences between the cards from the four clearance distributions are small. Below an engine speed of 1,000 r.p.m. the difference between the chamber and cylinder cards was less than the dispersion of the points on the Farnboro indicator record. In Figure 13 the maximum pressure difference thus indicated is 35 pounds per square inch at 1,500 r.p.m. The maximum pressure difference, in favor of the cylinder, occurs at approximately 20° B.T.C. The indicator cards are too indistinct at the tops to give any information as to the manner in which the chamber pressure finally rises higher than the cylinder pressure.

CONCLUSIONS

The results of this investigation show that for the design of combustion chamber used in these tests, the minimum auxiliary chamber volume for good performance is 35 per cent of the total clearance volume; for greater percentages, the

improvement in performance is slight. This size of precombustion chamber is advantageous because, compared to the other sizes, it has the lowest explosion pressures, medium rates of pressure rise, and least combustion knock.

The variation in precombustion chamber volume as the clearance distribution was varied had a negligible effect on f.m.e.p., compression pressures, and relative compression temperatures. However, this change in auxiliary chamber size with the resulting change in the total surface exposed to the gases of combustion does affect the heat losses to the cooling water and causes them to vary with the size of the precombustion chamber.

Variation of clearance distribution only for a fixed ratio of precombustion chamber volume to connecting passage area does not exercise sufficient control over combustion or eliminate combustion knock.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., October 26, 1932.

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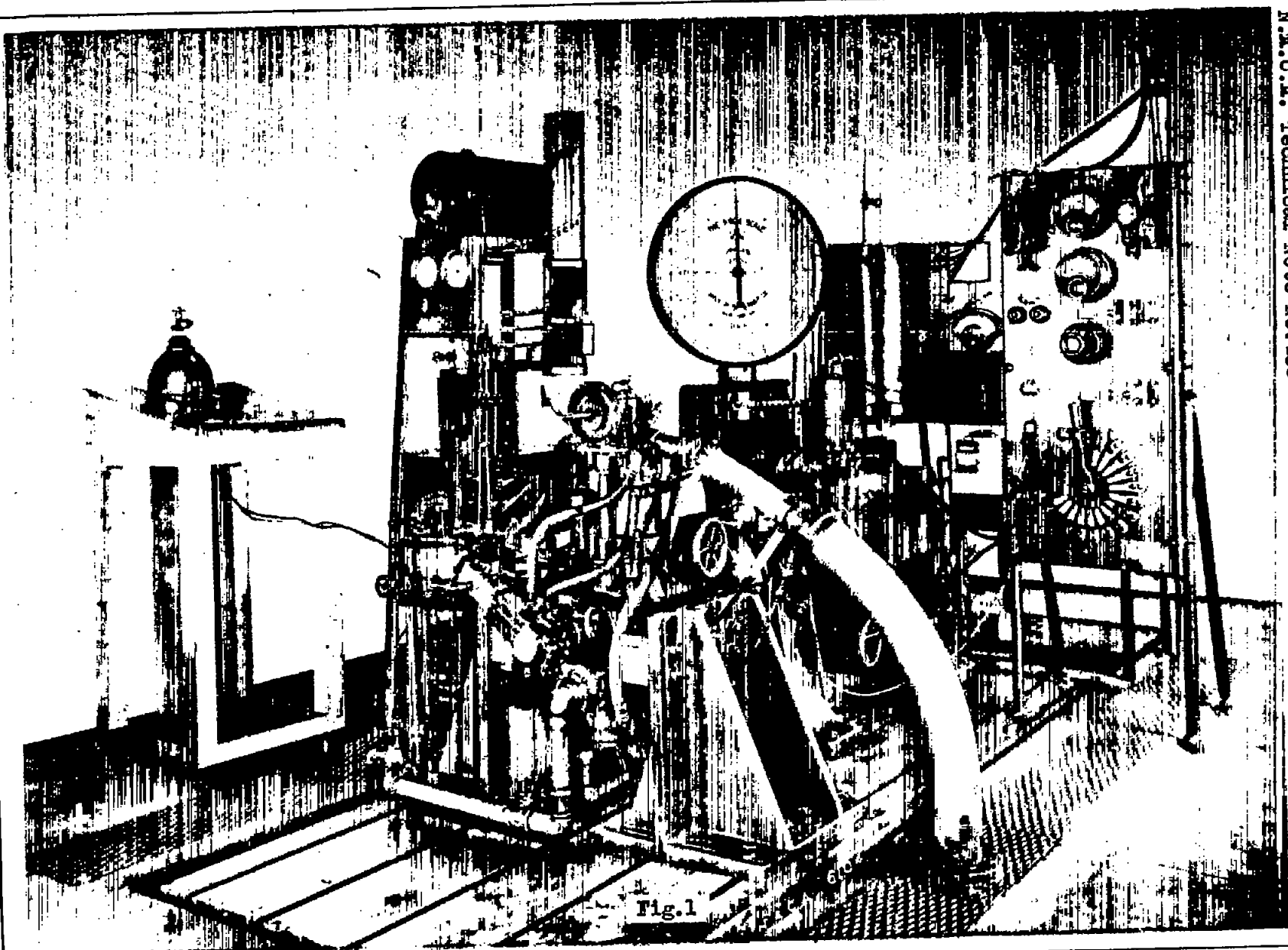


Fig. 1

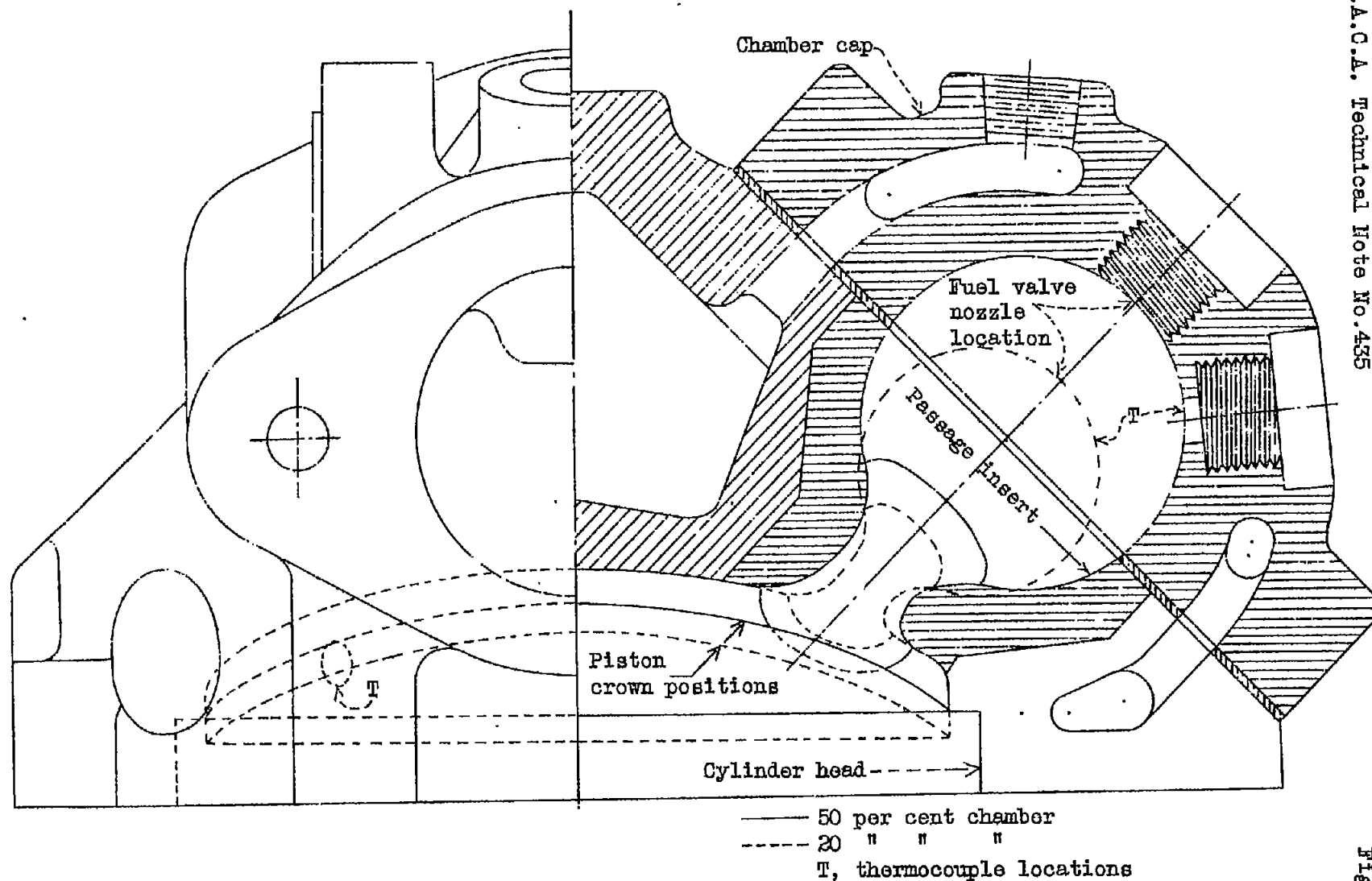


Fig. 2 Cylinder-head design, showing removable insert and two chamber outlines.

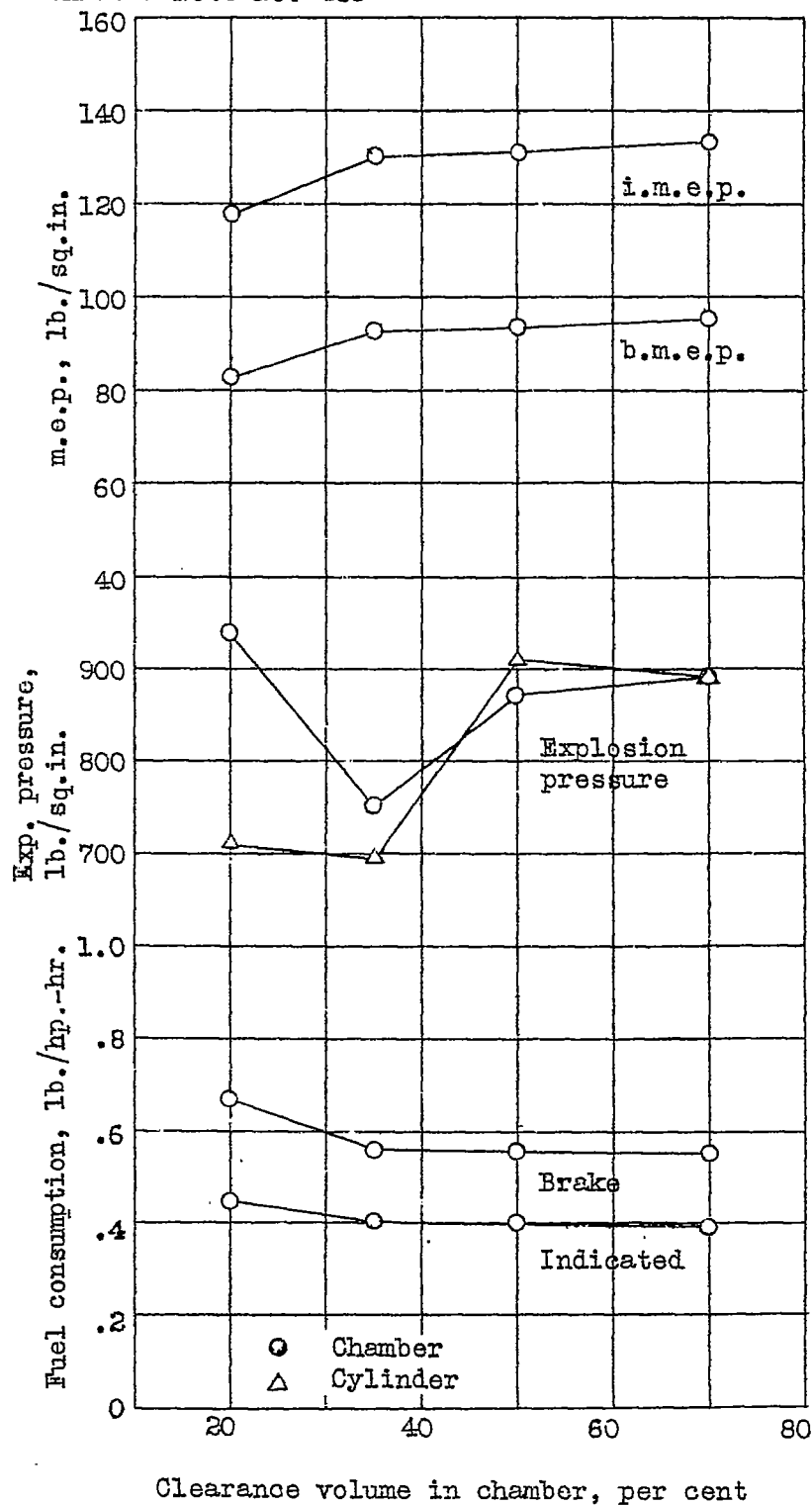


Fig. 3 Effect of clearance distribution on engine performance at 0.0003 lb. fuel/cycle, 12 percent excess air.

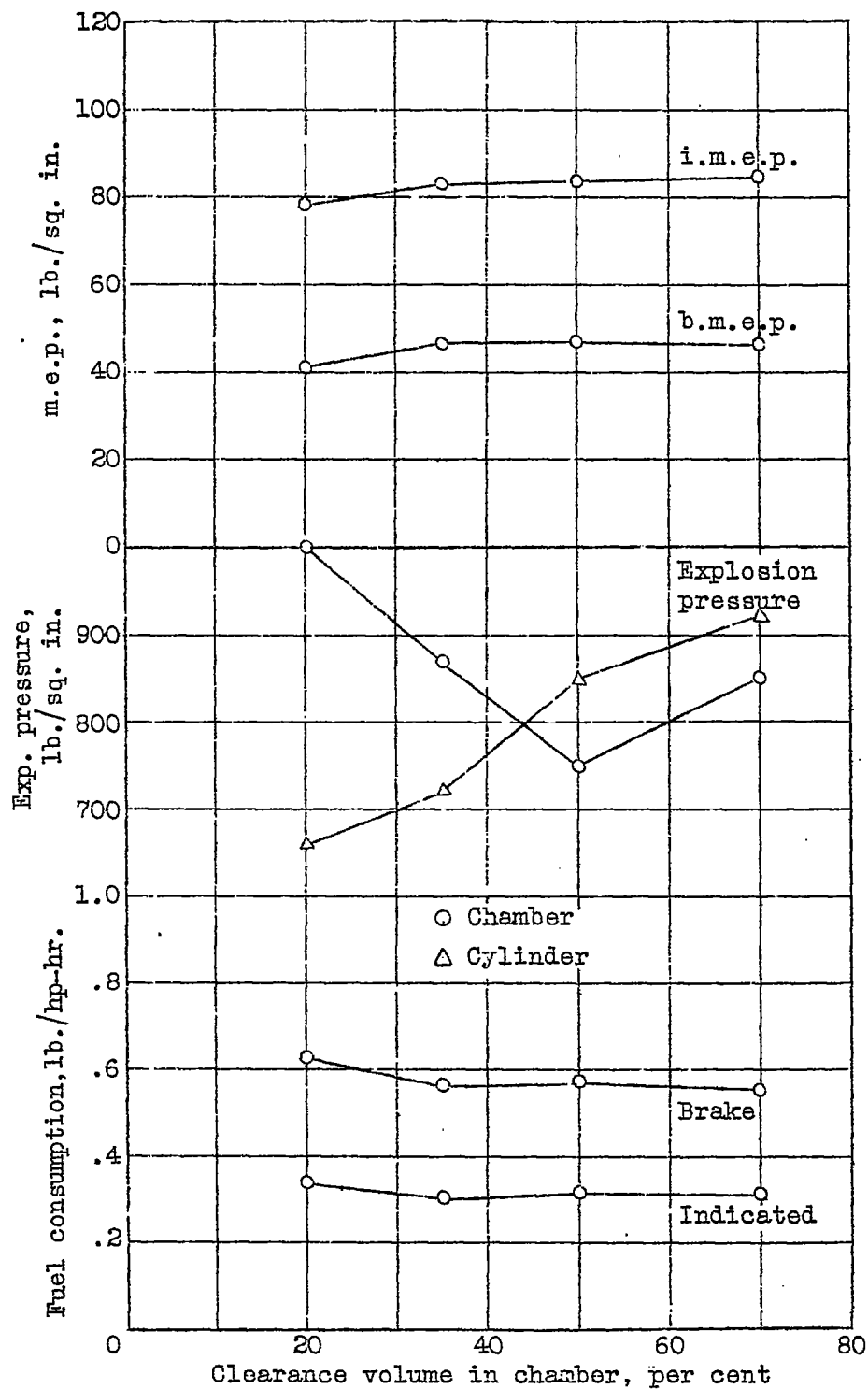


Fig.4 Effect of clearance distribution on engine performance at 0.00015 lb. fuel/cycle, 54 per cent excess air.

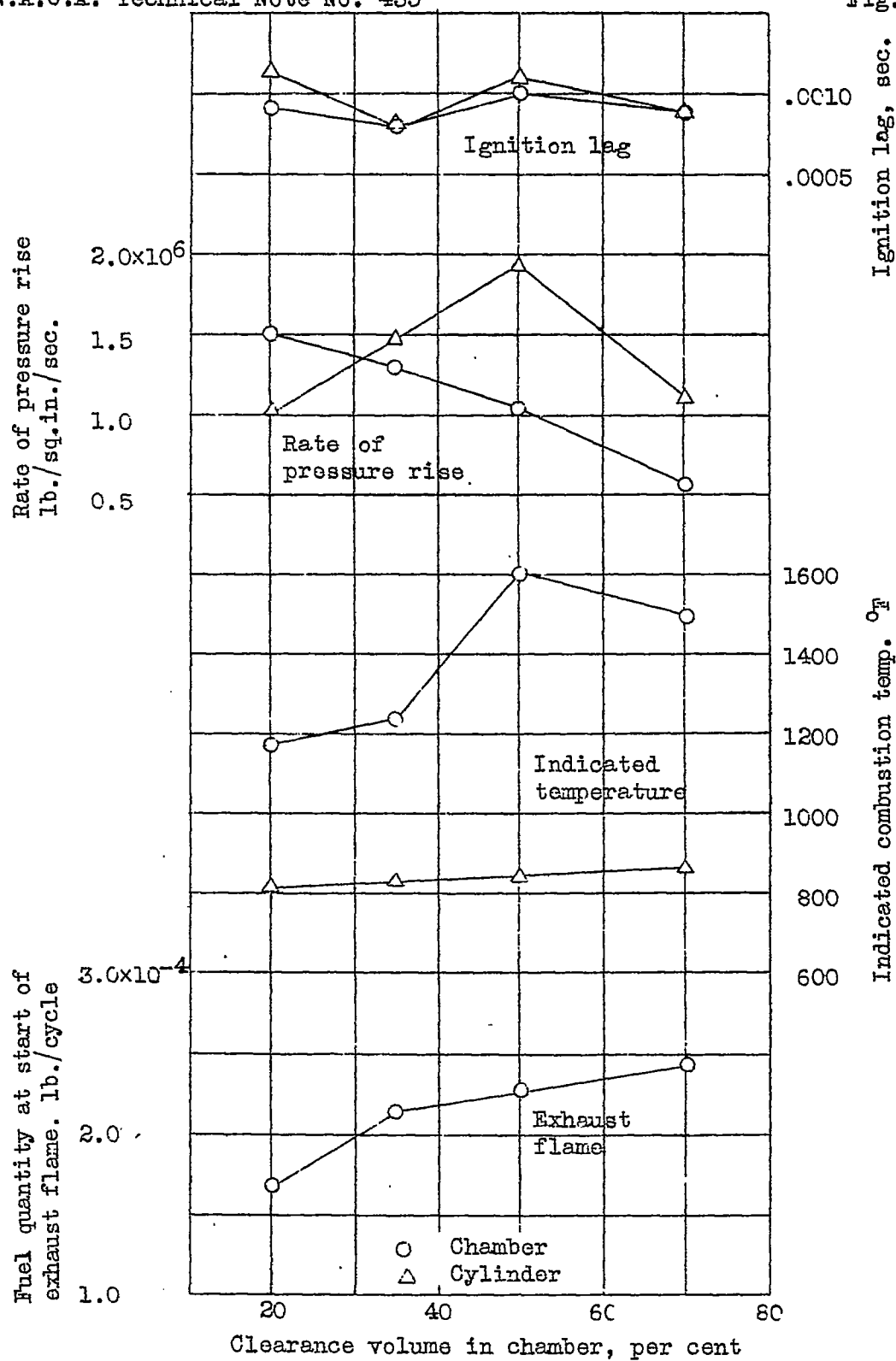


Fig. 5 Effect of clearance distribution on combustion characteristics

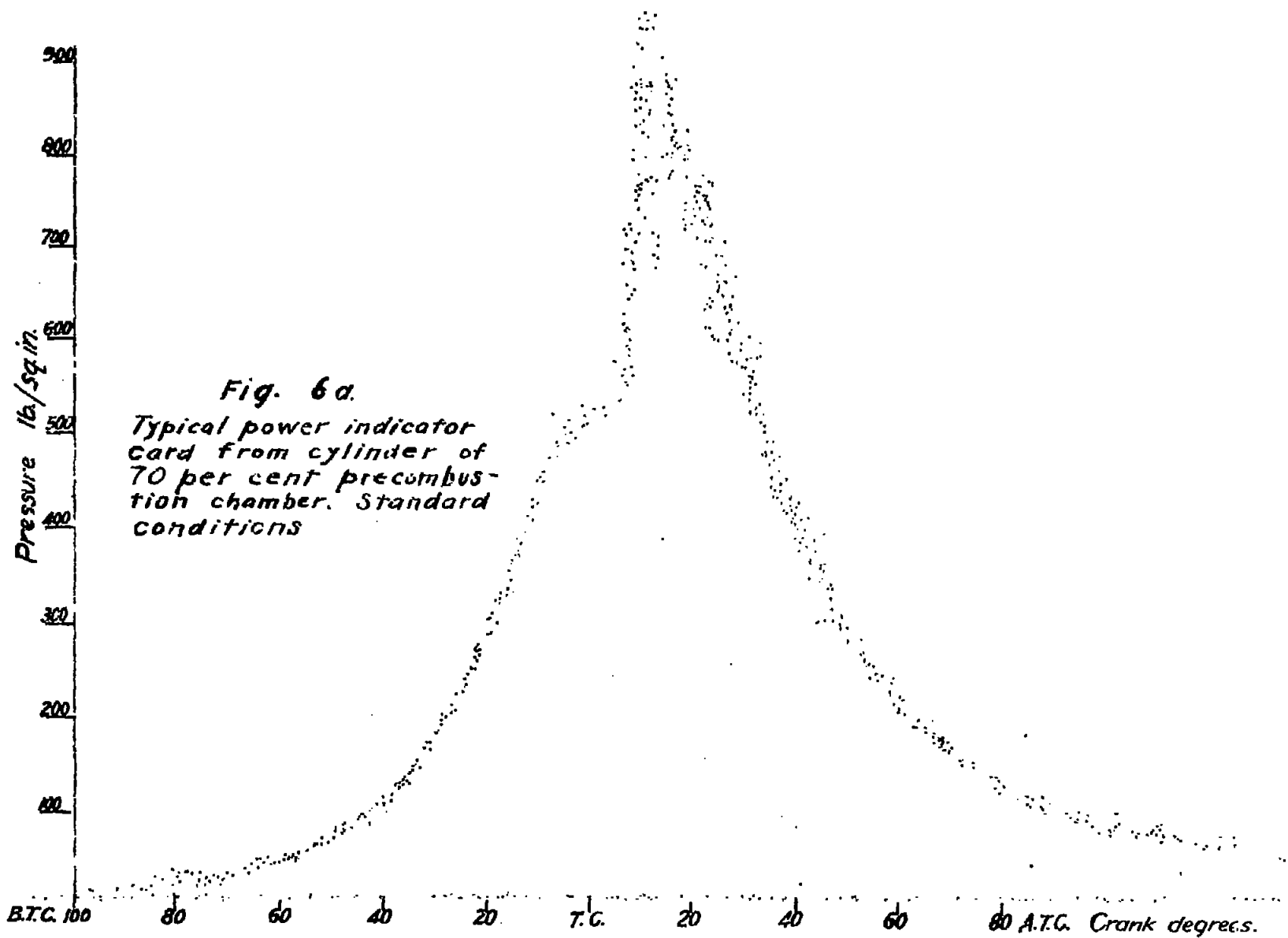


Fig. 6a

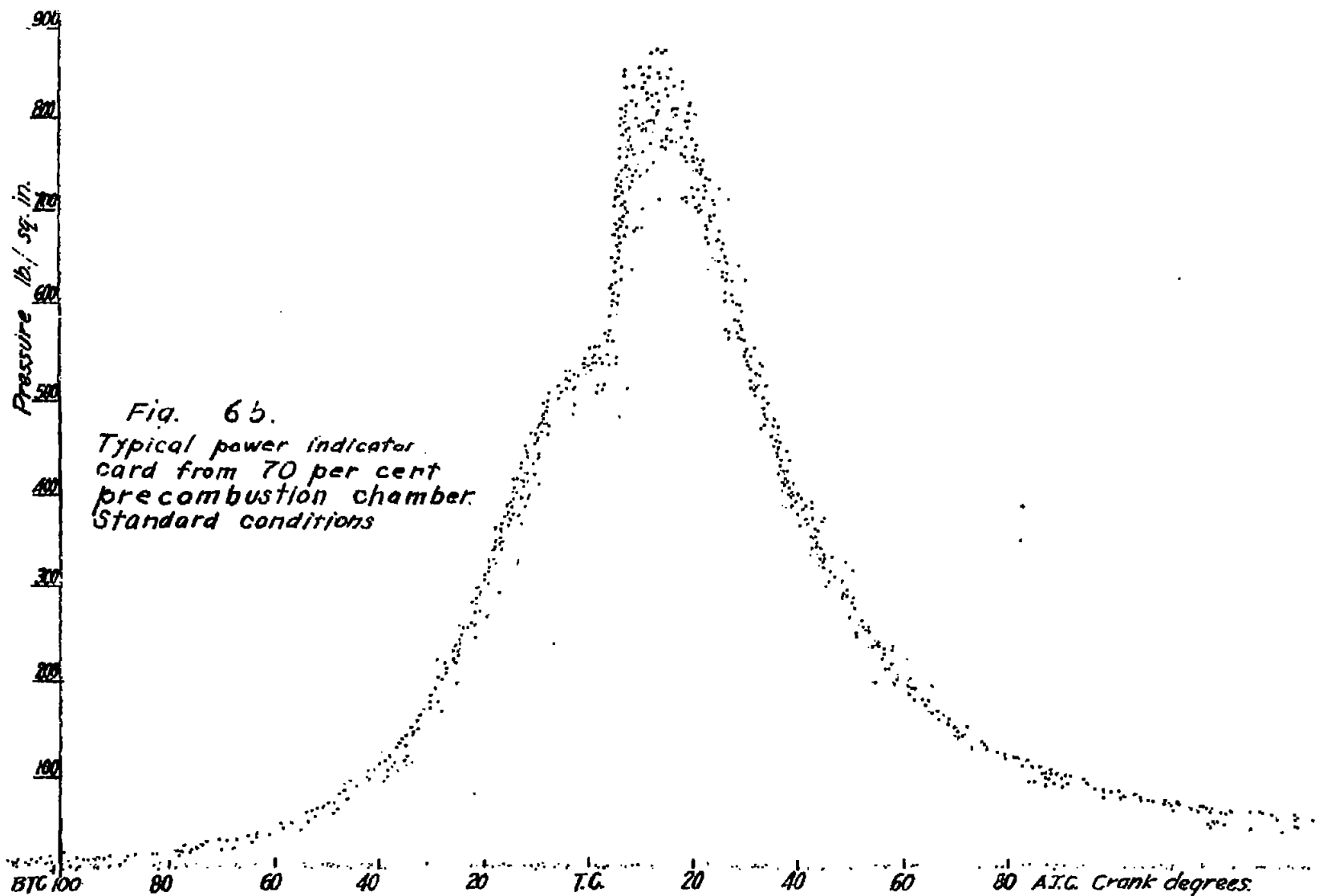


Fig. 6b.
Typical power indicator
card from 70 per cent
precombustion chamber
Standard conditions

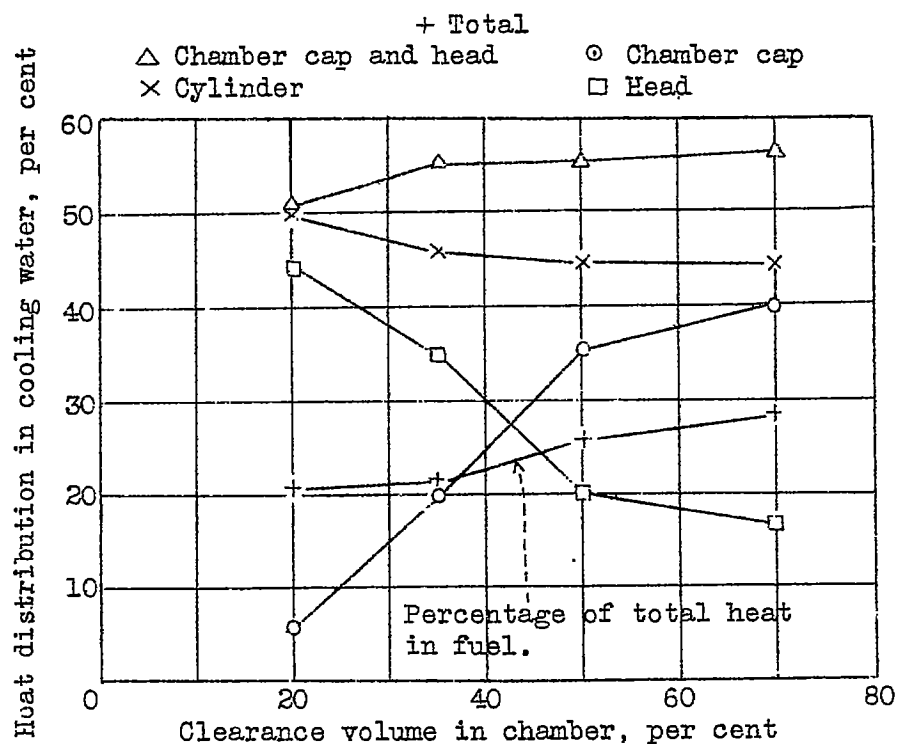


Fig.7a Effect of clearance distribution on heat loss to cooling water.

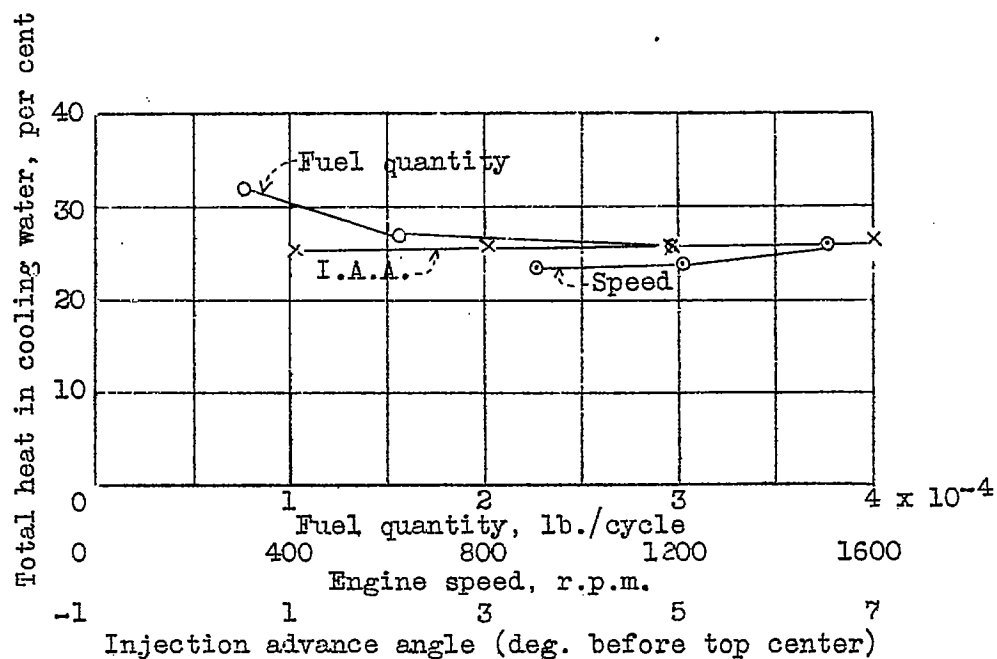


Fig.7b Effect of operating conditions on heat loss to cooling water, 50 per cent chamber.

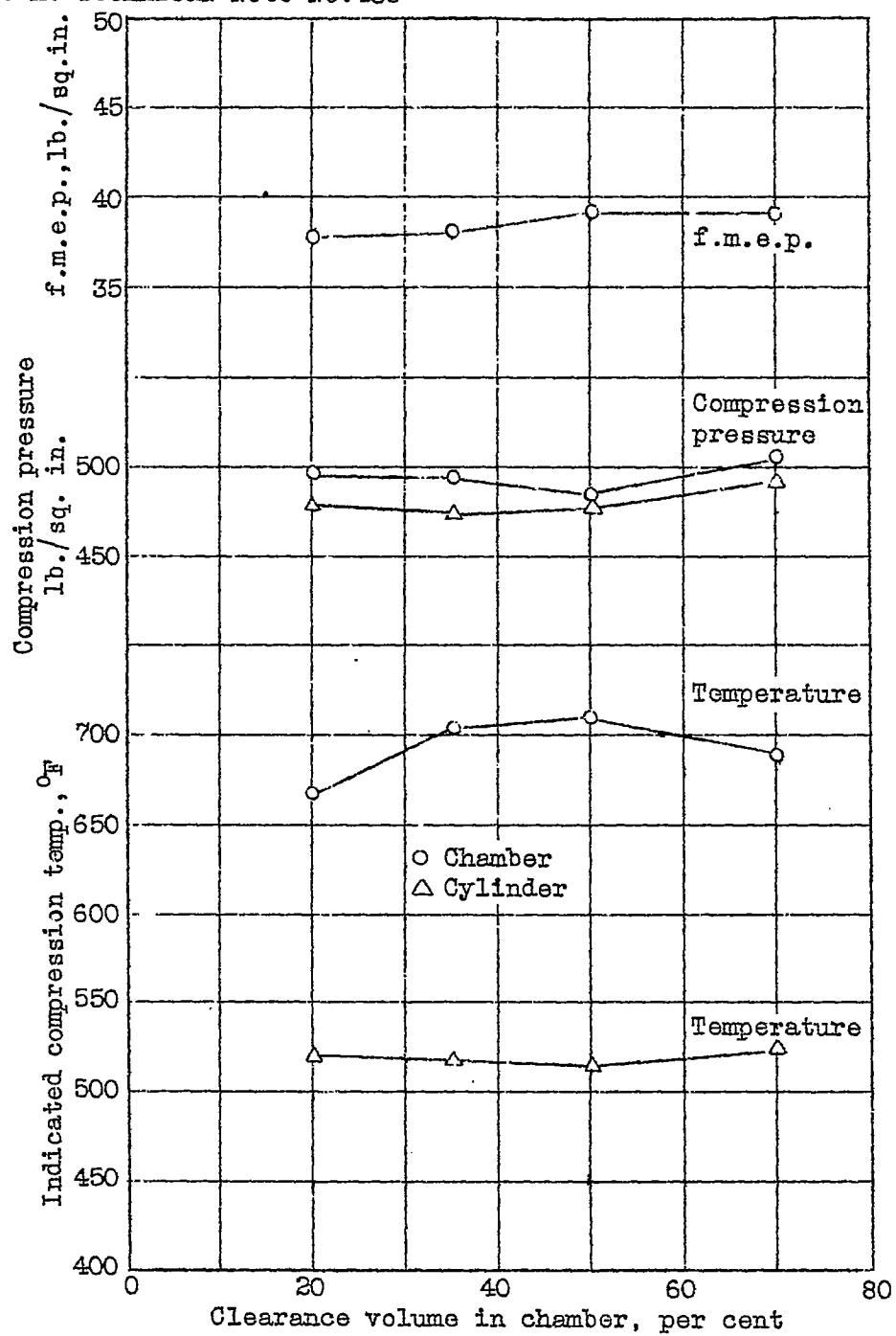


Fig.8 Effect of clearance distribution on motoring characteristics.

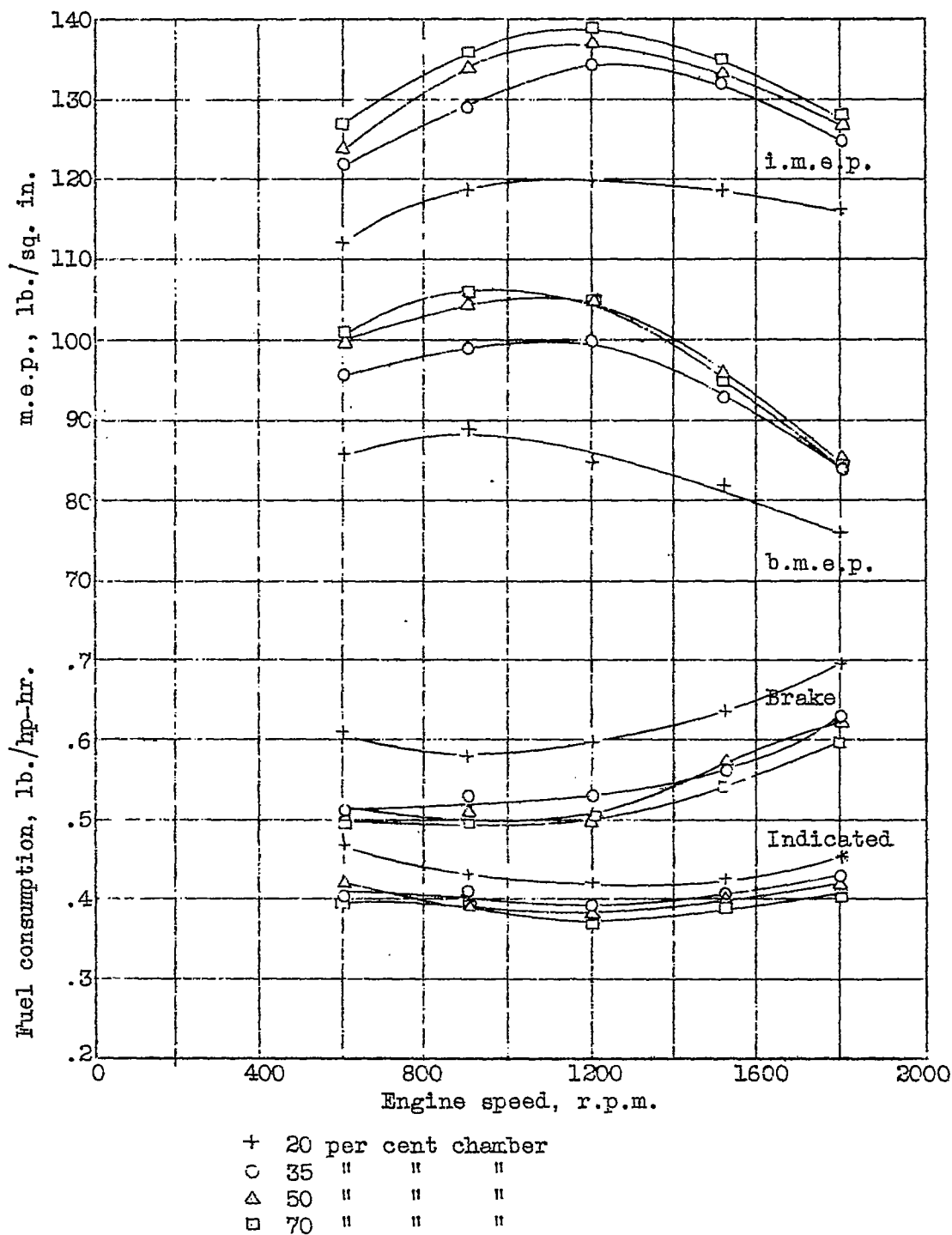


Fig.9 Effect of speed on mean effective pressures and fuel consumption.

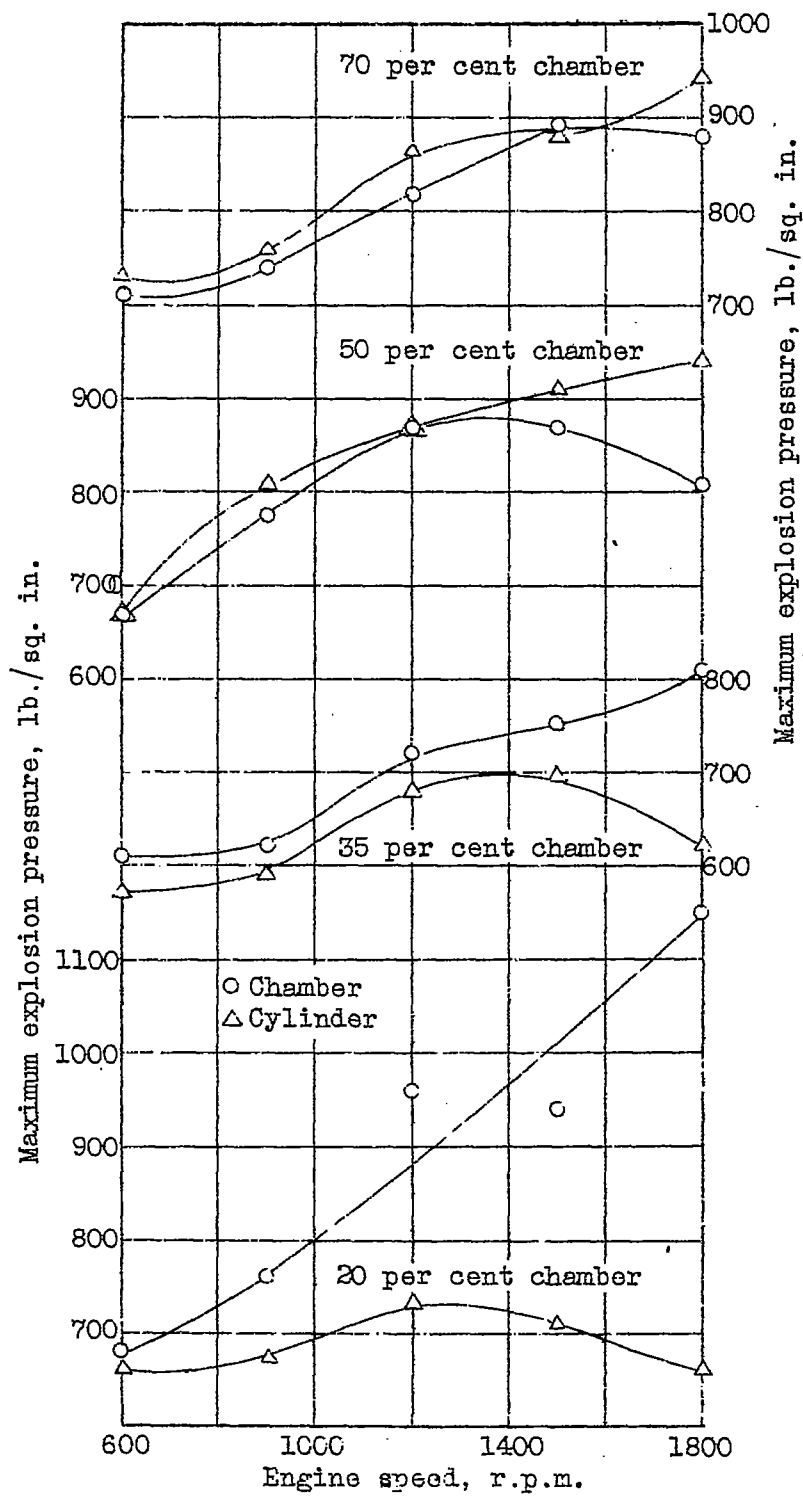


Fig.10 Effect of speed on maximum explosion pressure.

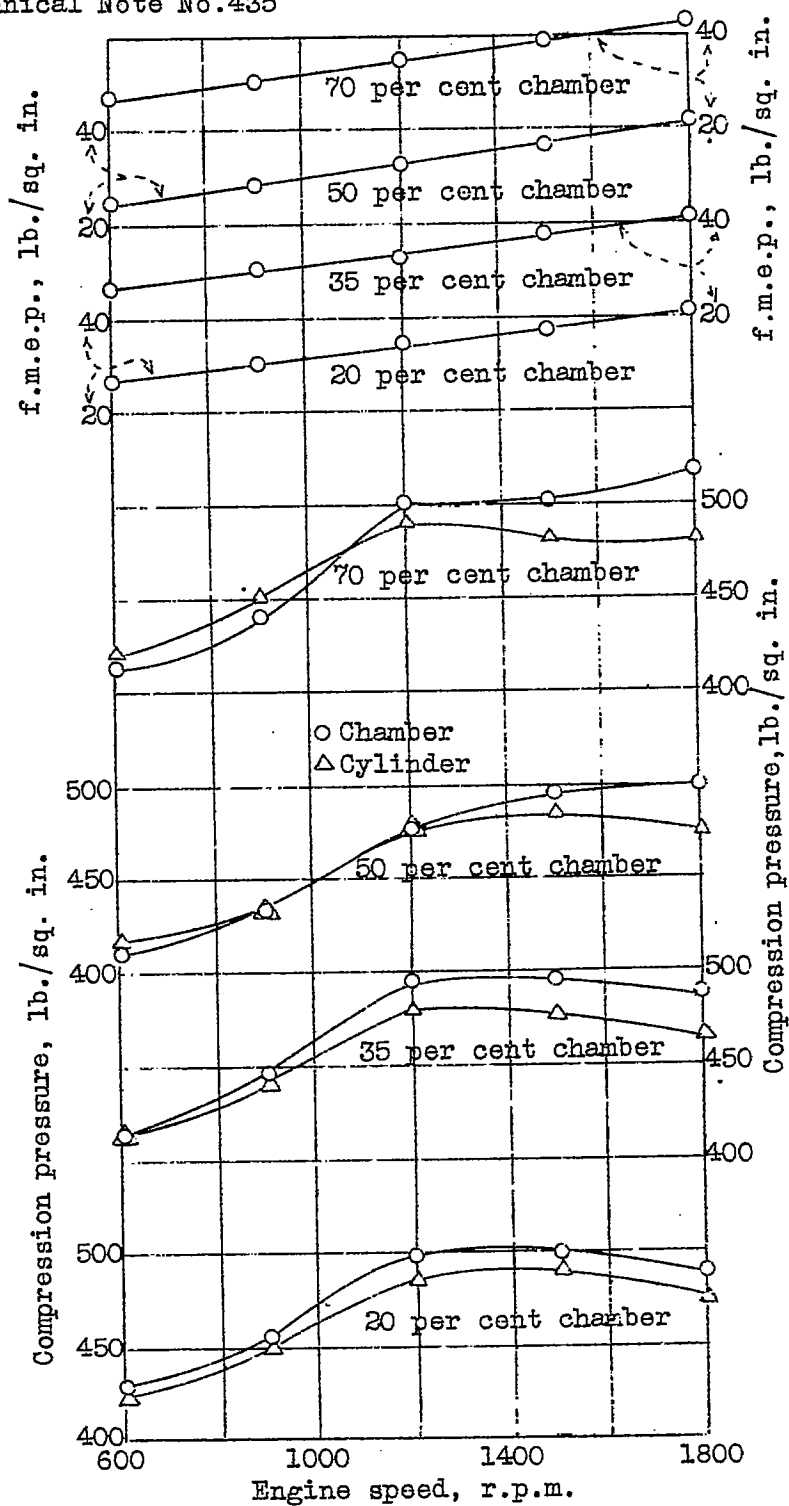


Fig.11 Effect of speed on compression pressure and friction mean effective pressure.

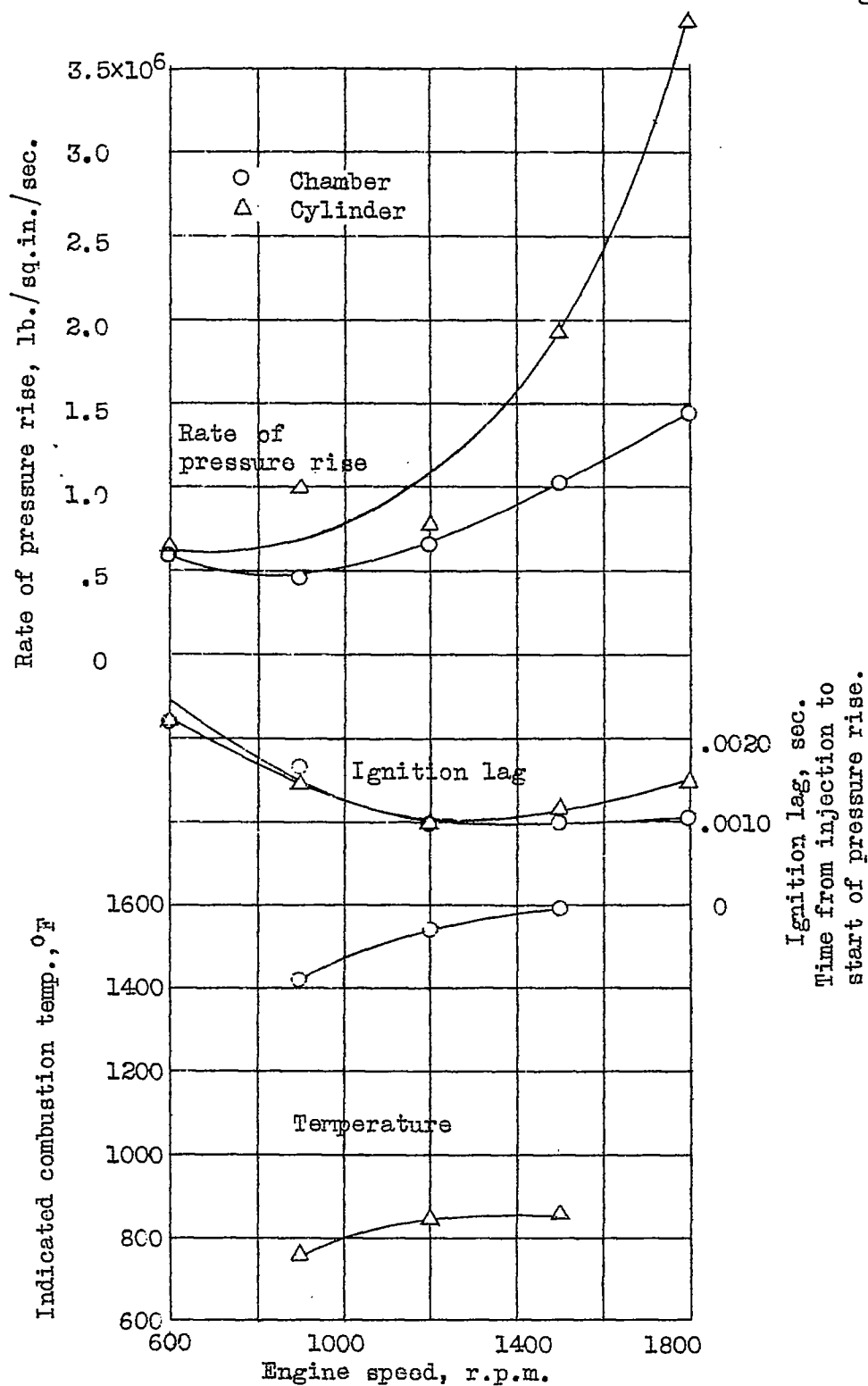


Fig. 12 Effect of speed on combustion characteristics, 50 per cent chamber.

